The Search for Colour Transparency

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Probing Nucleons and Nuclei via the (e,e'p) Reaction
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Outline

- Introduction
- Transparency & Colour Transparency (CT)
- Experimental Status
  - Review of Early experiments
  - Review of (e,e'p) experiments
  - Recent and Future Experiments
- Summary

Introduction

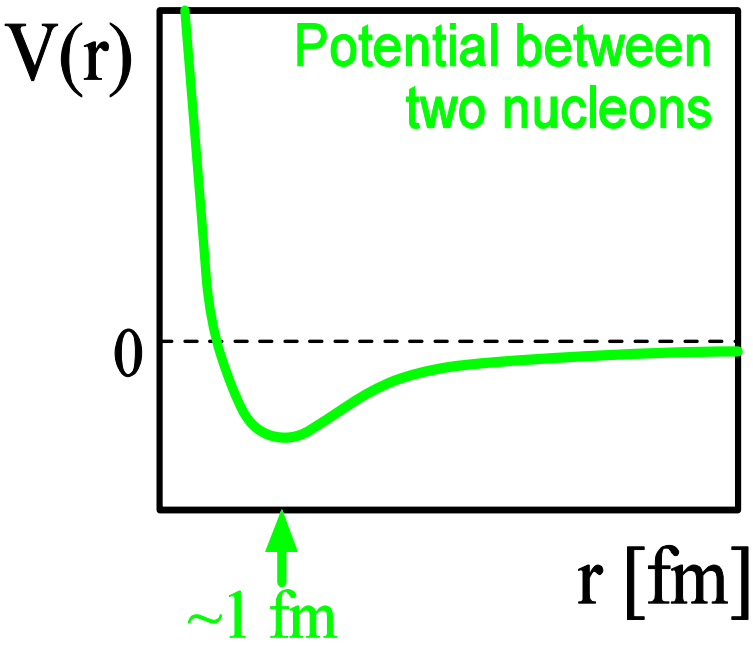
Quantum Chromo Dynamics (QCD): The fundamental theory describing the strong force in terms of quarks and gluons carrying colour charges.

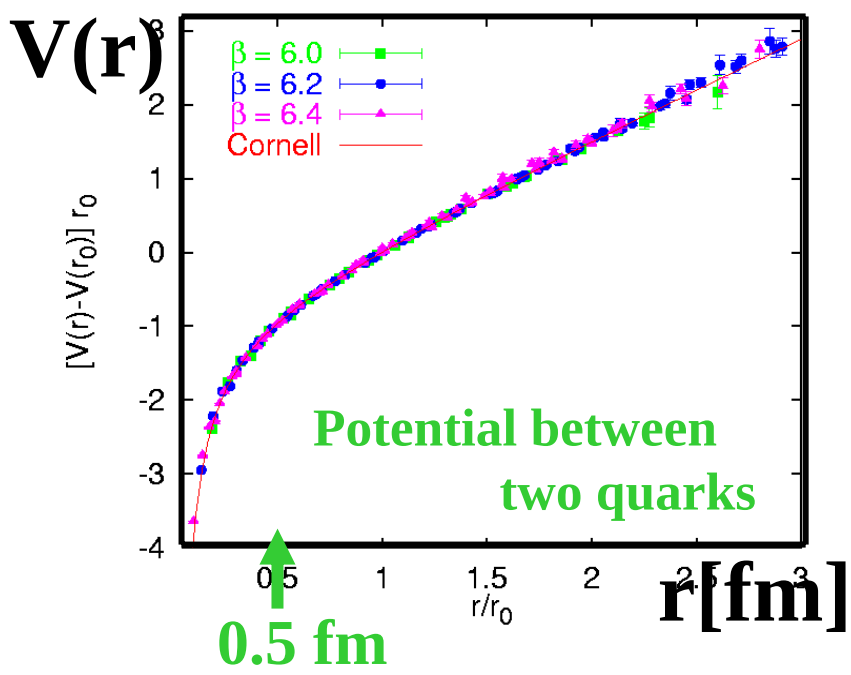
At short distances or high energies, QCD is asymptotically free ⇨ **Perturbative methods can be applied**

quarks and gluons in nucleons & nuclei are non-perturbative.

Understanding nucleons & nuclei in terms of quarks and gluons is the most important unsolved problem of the Standard Model of nuclear and particle physics.

Two "Realms" of Nuclear Physics



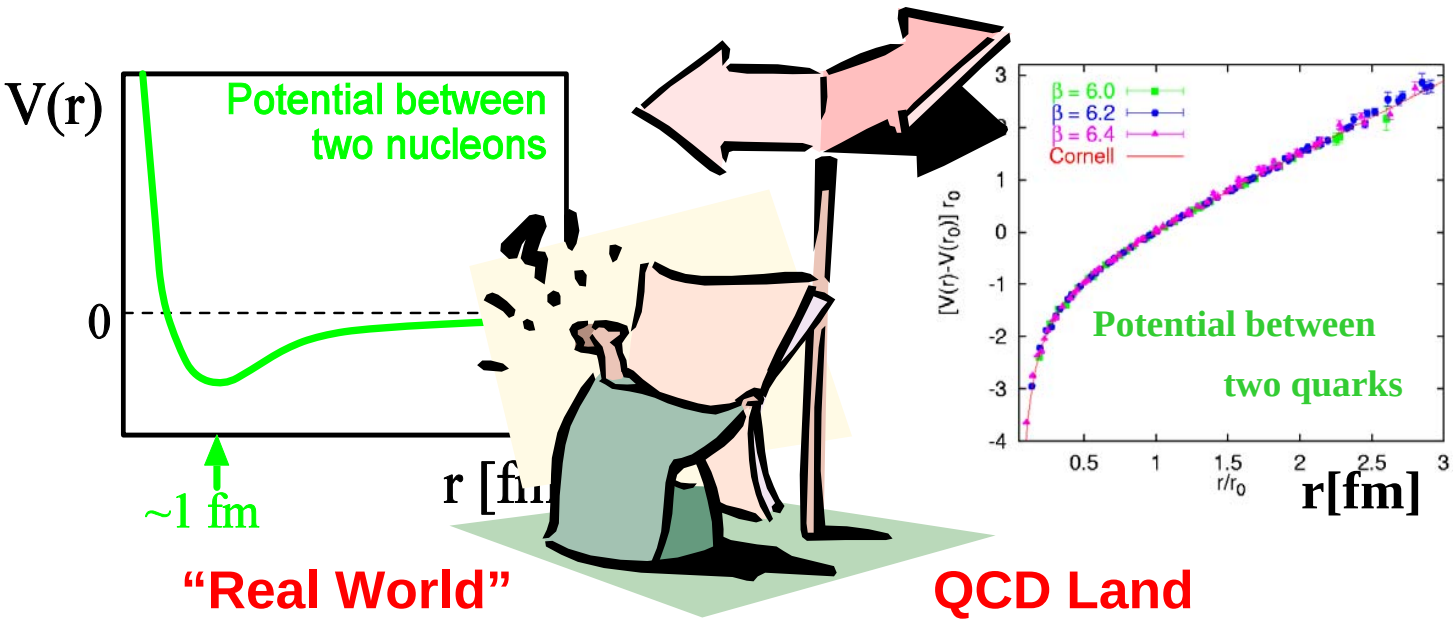


"Real World":
nucleons + mesons + interactions

QCD Land:
quarks + gluons + colour

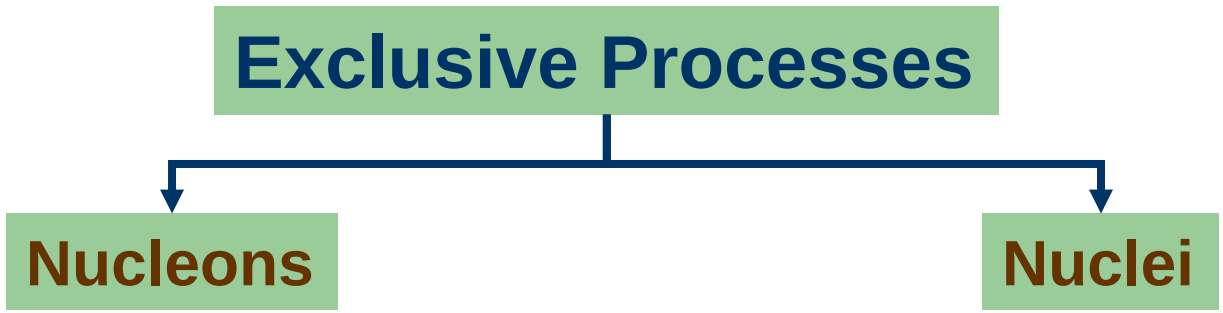
Two "Realms" of Nuclear Physics

Both realms are well understood but there is no roadmap from QCD land to the "Real world."



What Is the Energy Threshold for the Transition?

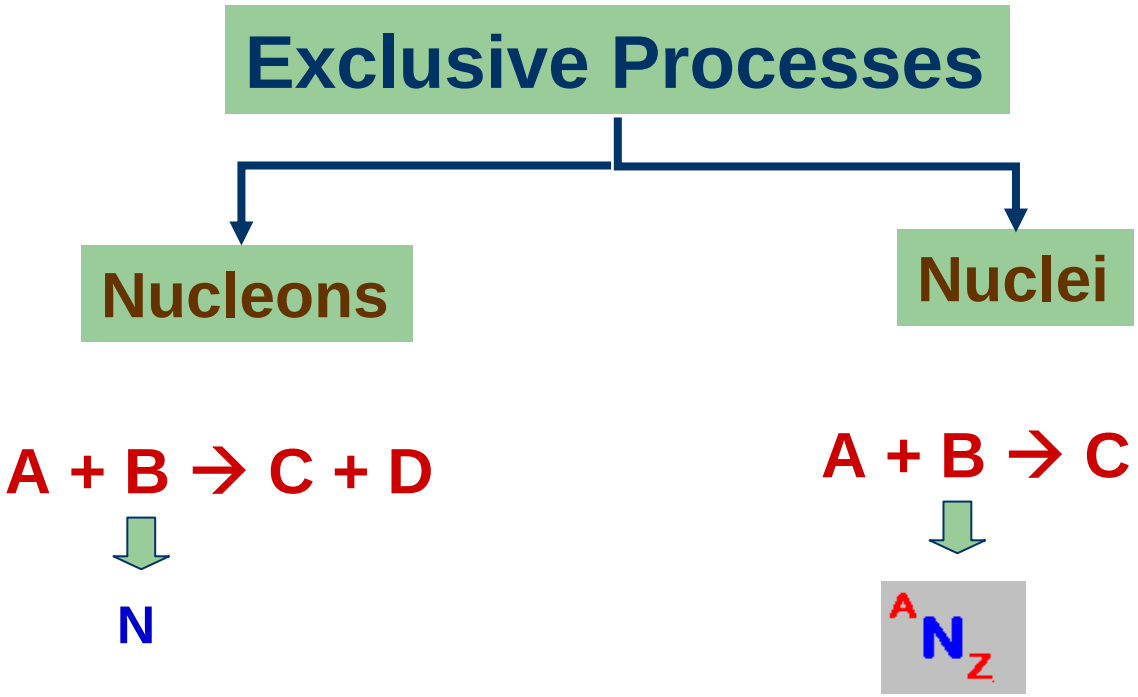
Exclusive processes (processes with completely determined initial and final states), are used to study the transition region.



- Quark counting rules
- Hadron helicity conservation

- Colour transparency
- Nuclear filtering

How Transparent is Your Nucleus?



Exclusive processes on nucleons and nuclei is used to measure transparency of nuclei

Nuclear Transparency

Ratio of cross-sections for exclusive processes from nuclei to nucleons is termed as Transparency

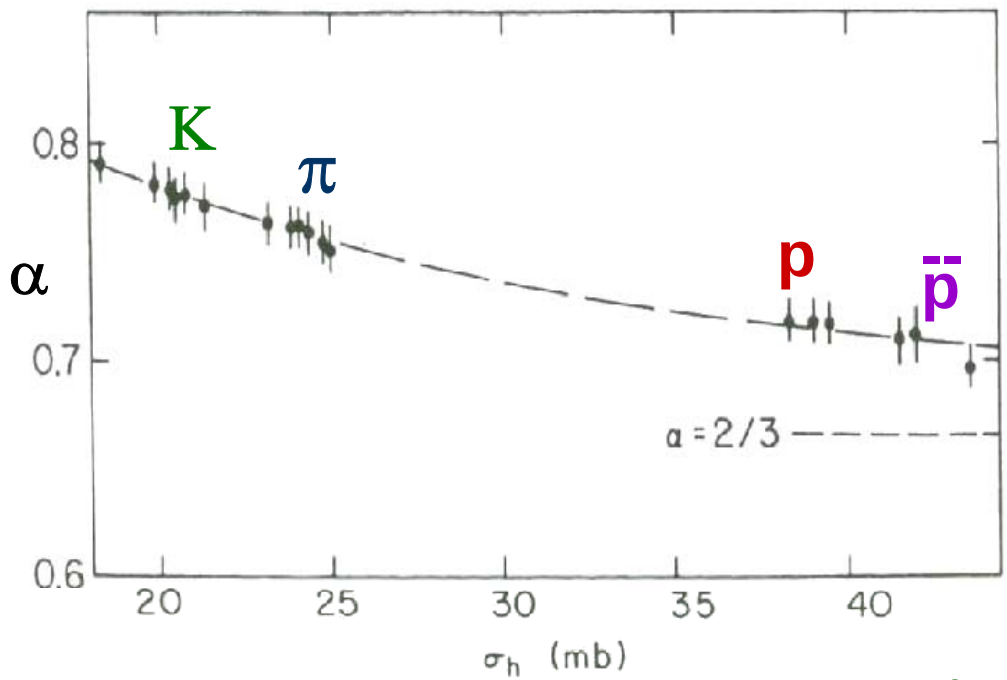
$$T = \frac{\sigma_N}{A\sigma_0}$$

σ_0 = free (nucleon) cross-section

σ_N parameterized as = $\sigma_0 A^{\alpha}$

Experimentally α = 0.72 – 0.78, for π, κ, p

Total Cross-sections



Hadron– Nucleus total cross-section

Fit to $\sigma(A) = \sigma_0 A^{\alpha}$

Hadron momentum 60, 200, 250 GeV/c

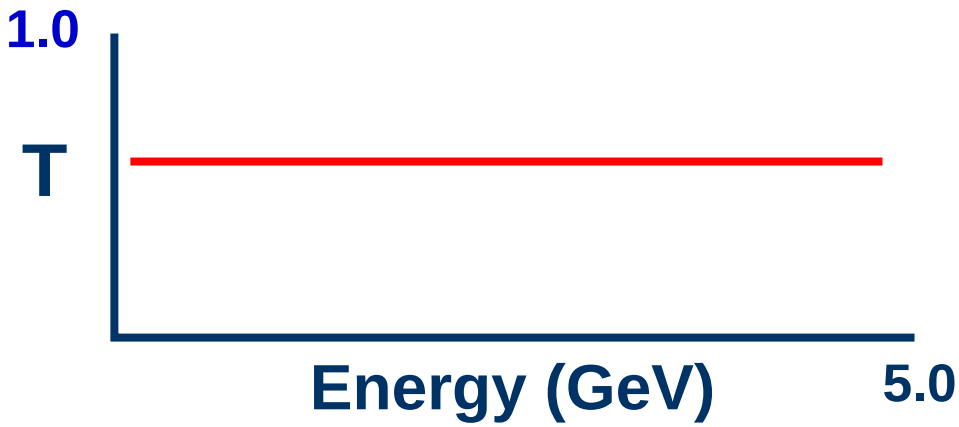
α = 0.72 – 0.78, for π, κ, p

α < 1 interpreted as due to the strongly interacting nature of the probe

A. S. Carroll *et al.* Phys. Lett 80B 319 (1979)

Nuclear Transparency

Traditional nuclear physics calculations (Glauber calculations) predict transparency to be energy independent .



Ingredients

- σ_{hN} h-N cross-section
- Glauber multiple scattering approximation
- Correlations & FSI effects.

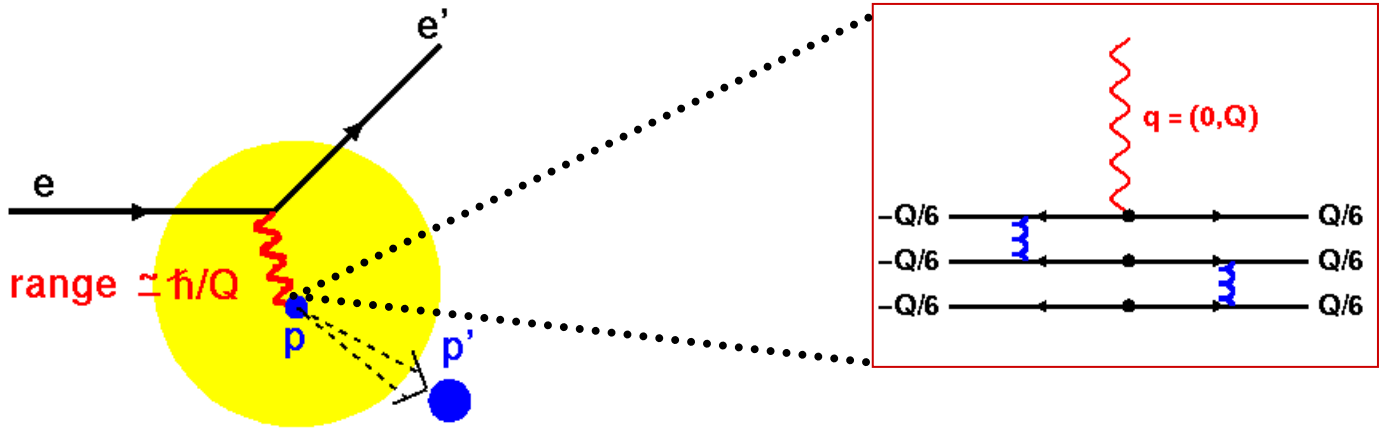
For light nuclei very precise calculations of are possible.

Colour Transparency

CT refers to the vanishing of the h-N interaction for h produced in exclusive processes at high Q

- **At high Q , the hadron involved fluctuates to a small transverse size – called the PLC (quantum mechanics)**
- **The PLC remains small as it propagates out of the nucleus (relativity).**
- **The PLC experiences reduced attenuation in the nucleus – it is color screened (nature of the strong force).**

Why is the PLC Selected Out?



Using e-p scattering as an example

- The momentum is distributed roughly equally among the quarks, (for it to be elastic scattering) ⇨ lifetime ≅ $\hbar/cQ$

⇨ range ≅ $\hbar/Q$

- At high Q an elastic interaction can occur only if the transverse size of the hadron involved is smaller than the equilibrium size.

Colour Screening and Lifetime of the PLC

The lifetime of the PLC is dilated in the frame of the nucleus

$$\gamma t_f = \frac{E}{m} t_f$$

The PLC can propagate out of the nucleus before returning to its equilibrium size.

The colour field of a color neutral object vanishes with decreasing size of the object .

$$\sigma_{PLC} \approx \sigma_{hN} \frac{b^2}{R_h^2}$$

(Analogues to electric dipole in QED)

Colour Transparency - Experimental Status

h can be : $q\bar{q}$ system (e^+e^- in QED)
qqq system (unique to QCD)

- **Colour Transparency in A(p,2p) BNL**
- **Colour Transparency in A(π^-,π^0)A' IHEP**
- **Colour Transparency in A(e,e'p) SLAC, JLab**
- **Colour Transparency in A(l,l' r) FNAL, HERMES**
- **Colour Transparency in di-jet production FNAL**
- **Colour Transparency in A(e,e'p) JLab**
- **Colour Transparency in A(g,p π), A(e,e' π) JLab**

Review of the First CT Searches

First experiment to look for color transparency

Experiment performed at Brookhaven

Using:

Proton knockout

$$p + A \rightarrow p + p + X$$

&

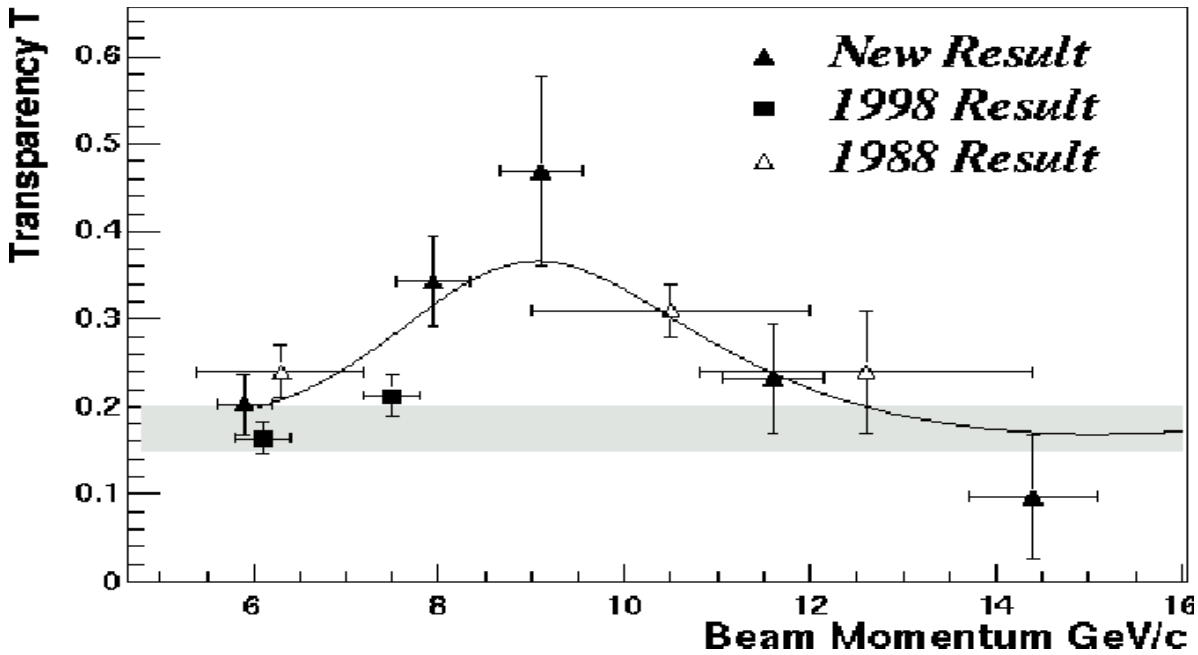
$$p + p \rightarrow p + p$$

$$T = \frac{\sigma_{pA}}{A\,\sigma_{pp}}$$

A. S. Carroll et al., PRL 61, 1698 (1988)
I. Mardor et al., PRL 81, 5085 (1998)
A. Leksanov et al., PRL 87, 212301 (2001)

Transparency in A(p,2p) Reaction

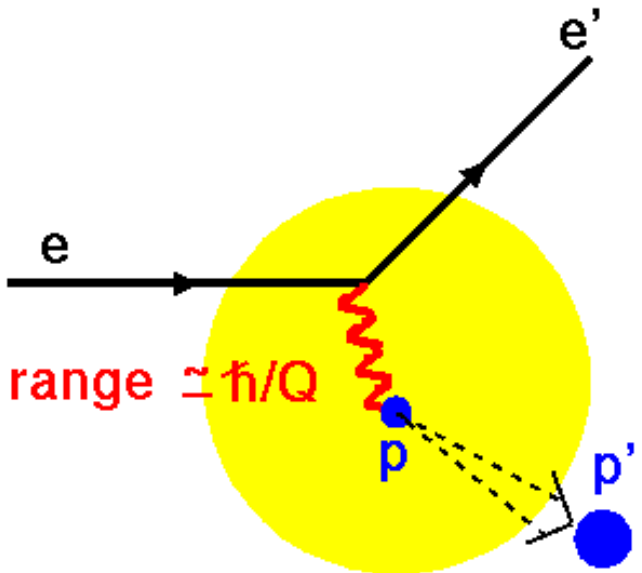
First experiment to look for color transparency



Results inconsistent with CT but explained in terms of nuclear filtering or charm resonance states.

Transparency in A(e,e'p) Reaction

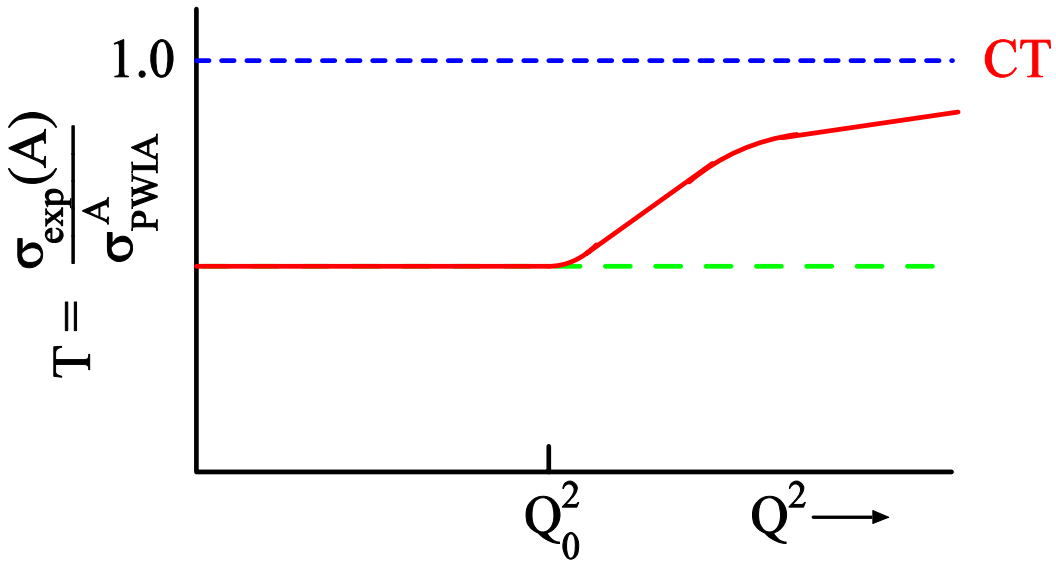
The prediction of CT implies: Fast protons have reduced final state interactions.



e + A → e' + p + X

Transparency in A(e,e'p) Reaction

The prediction of CT implies: Fast protons have reduced final state interactions.



$e + A \rightarrow e' + p + X$

Q^2 is square of the momentum transfer

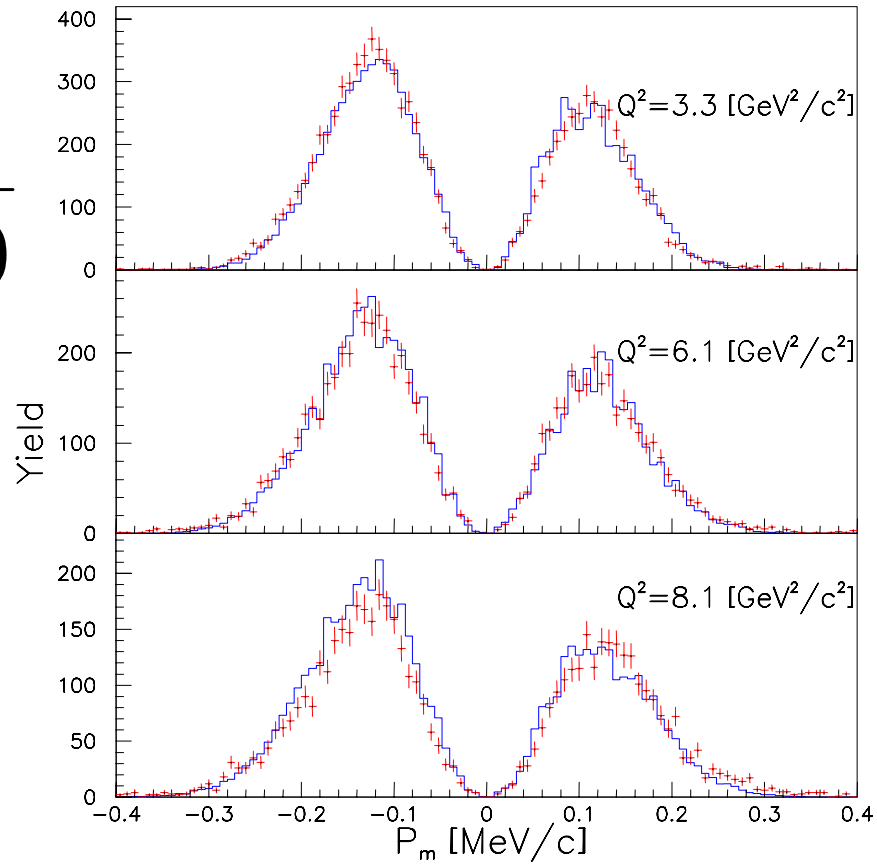
Transparency in A(e,e'p) Reaction

$$T = \frac{\int dP_m dE_m N_{Exp}(E_m, P_m)}{\int dP_m dE_m N_{PWIA}(E_m, P_m)}$$

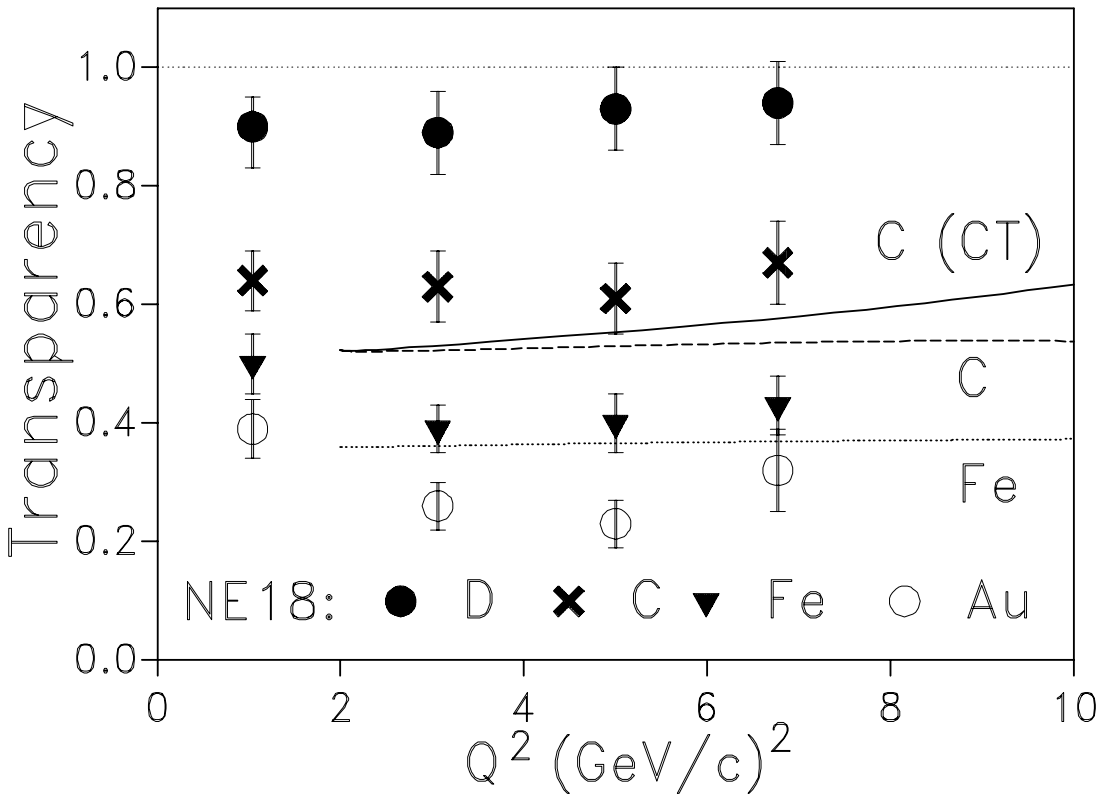
Experimental Yield in Red

&

Simulated Yield in Blue



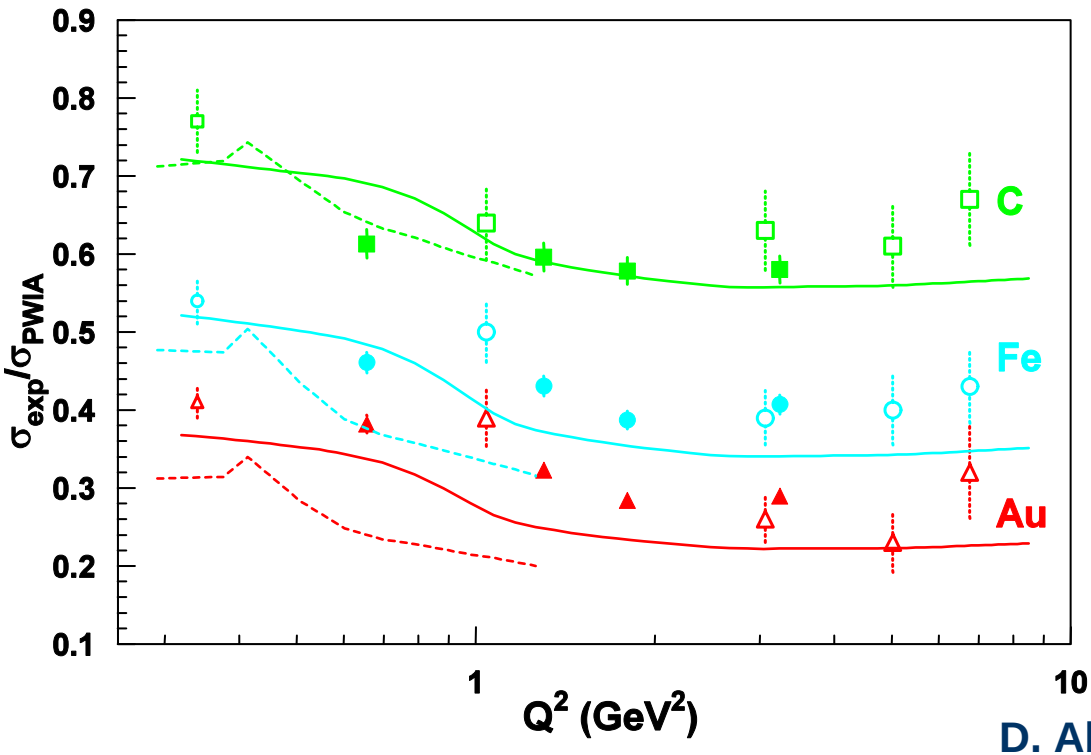
The SLAC – NE18 Experiment



N.C.R.Makins et al., PRL 72, 1986 (1994)
T.G.O'Neill et al., PLB 351, 87 (1995)

Where is the Baseline for CT studies?

JLab E91013, (e,e'p) on C, Fe, Au



Glauber

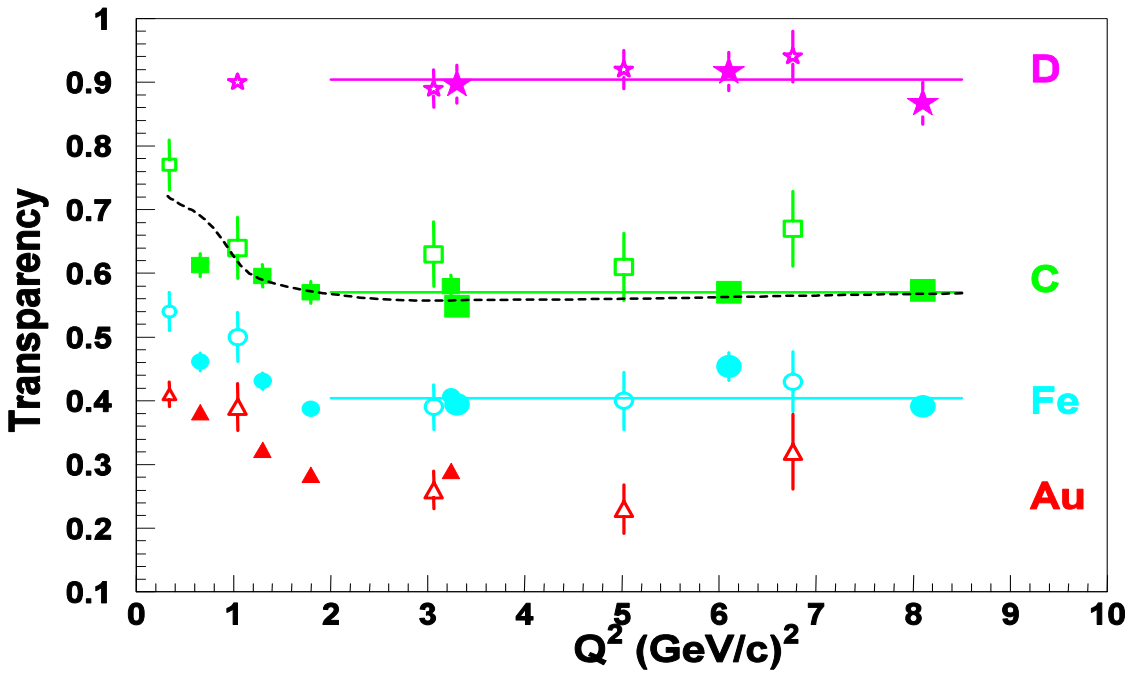
DWIA

Open symbols - NE18
Solid symbols - E91013

D. Abbott et al. PRL 80, 5072 (1998)

A(e,e'p) Results

Q^2 dependence consistent with standard nuclear physics calculations



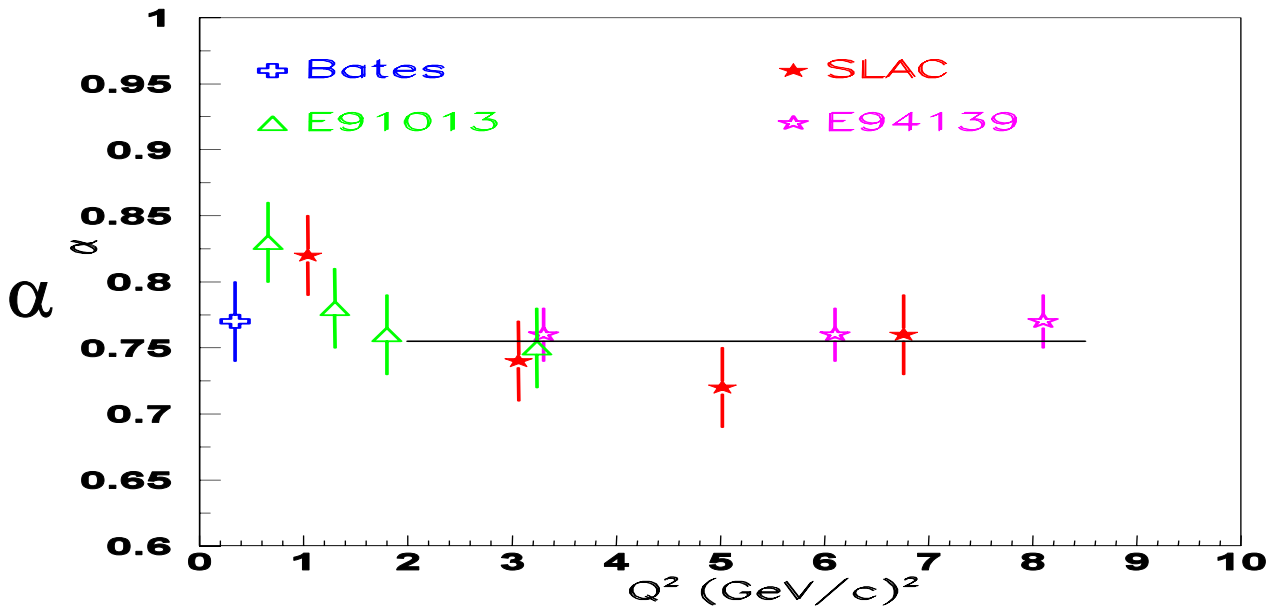
Solid Pts – JLab
Open Pts -- other

Constant value fit for $Q^2 > 2$ (GeV/c)^2 has $\chi^2/df \cong 1$

K. Garrow et al. PRC 66, 044613 (2002)

A(e,e'p) Results -- A Dependence

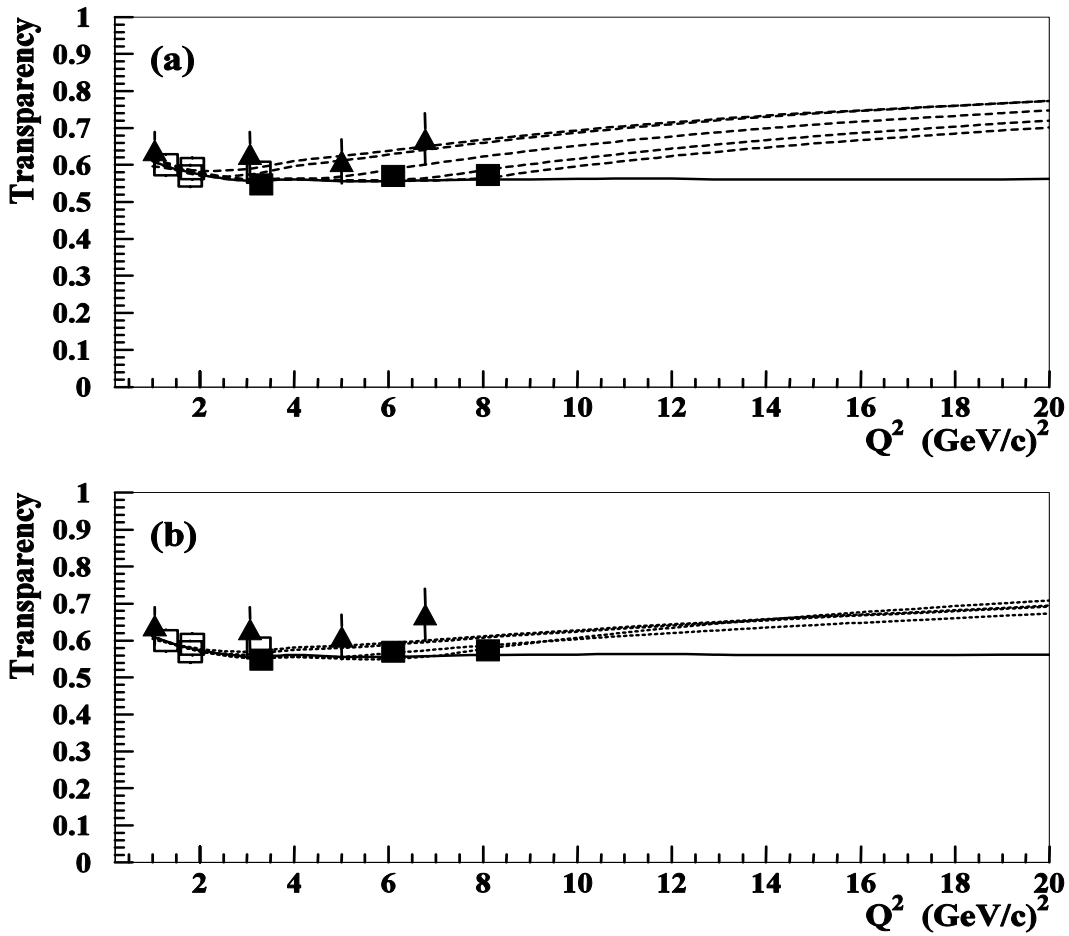
Fit to $\sigma = \sigma_0 A^{\alpha}$



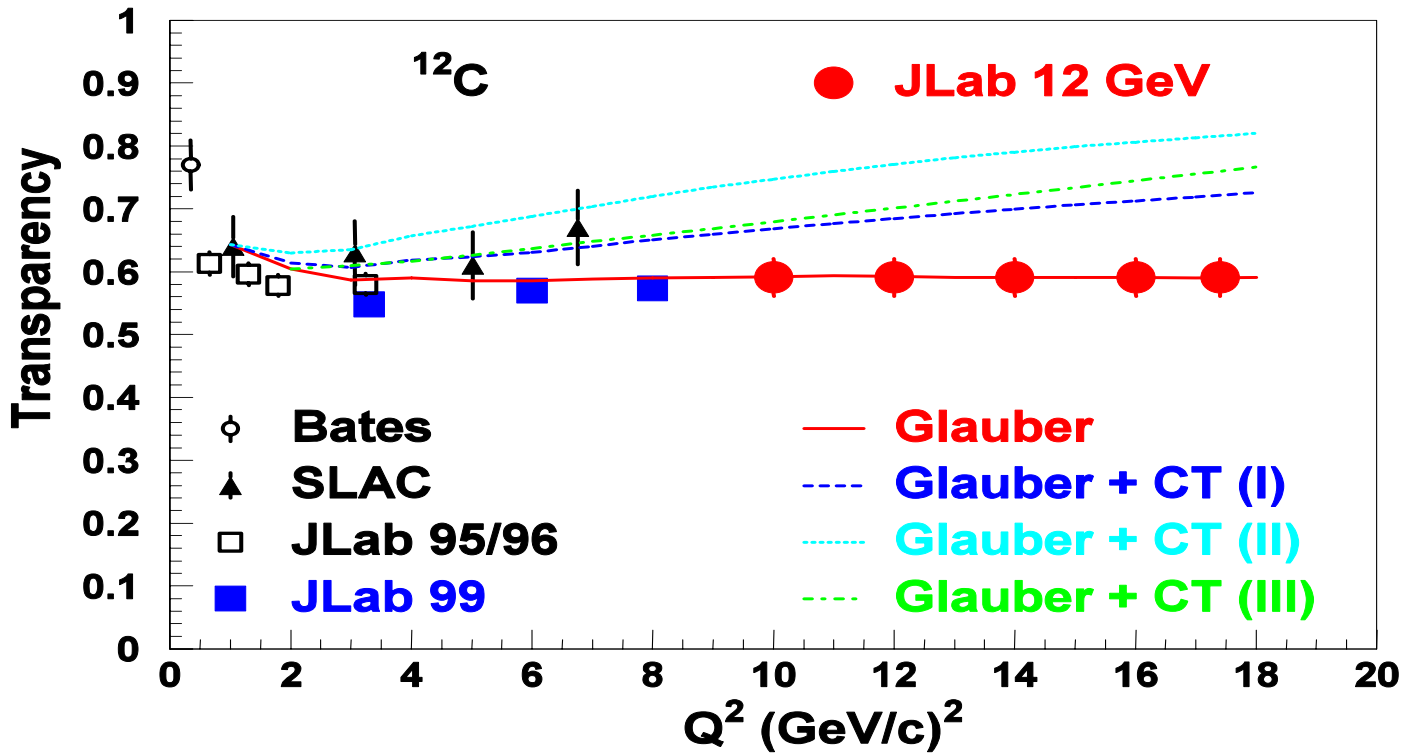
α = constant = 0.76

for $Q^2 > 2$ $(GeV/c)^2$

New Limits for CT in A(e,e'p)



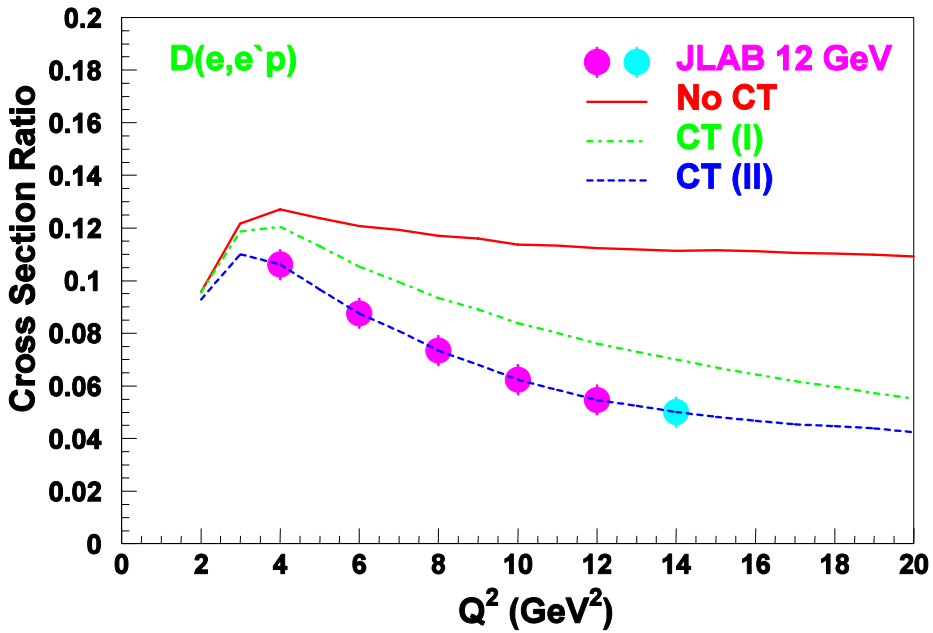
A(e,e'p) at 12 GeV



With HMS and SHMS @ 12 GeV

D(e,e'p) at Large Missing Momentum

CT → reduction in rescattering of the struck nucleon, which dominates events with Pm > Fermi momentum



Ratio of cross-section at Pm = 400 MeV/c to cross-section at Pm = 200 MeV/c is sensitive to CT

qqq vs $q\bar{q}$ systems

- There is no unambiguous, model independent, evidence for CT in qqq systems.
- Small size is more probable in 2 quark system such as pions than in protons.

(B. Blattel et al., PRL 70, 896 (1993)

- Onset of CT expected at lower Q^2 in $q\bar{q}$ system.
- Formation length is ~ 10 fm at moderate Q^2 in $q\bar{q}$ system.

Review of the First CT Searches

First experiment to claim color transparency

Using: $\pi^- + A \rightarrow \pi^0 + A'$ **on** ^{12}C **&** ^{1}H

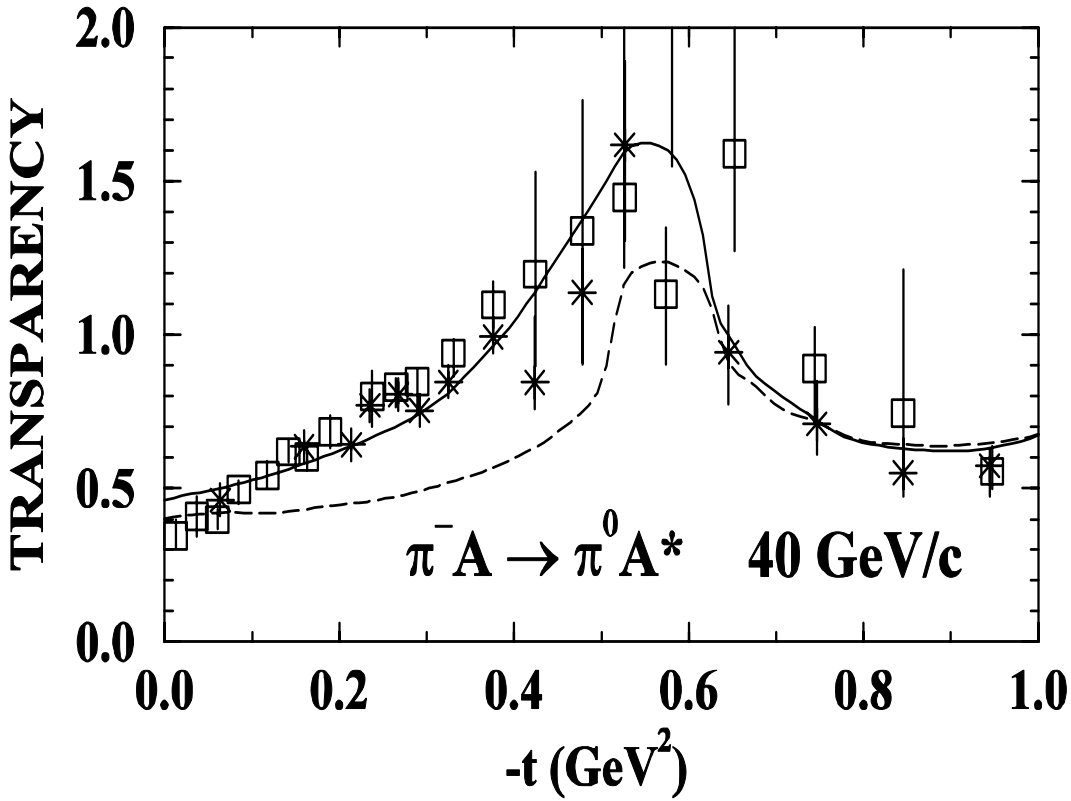
Quasifree charge exchange

$$T = \frac{\sigma_{\pi A}}{A\,\sigma_{\pi p}}$$

Experiment performed at IHEP at 40 GeV

V. D. Apokin et al. , SJNP 36, 1698 (1982) , SJNP 46, 1108 (1987)
B. Z. Kopeliovich et al., SJNP 46, 1535 (1987), PLB 264, 434 (1991)

Quasi-elastic Charge Exchange with Pions

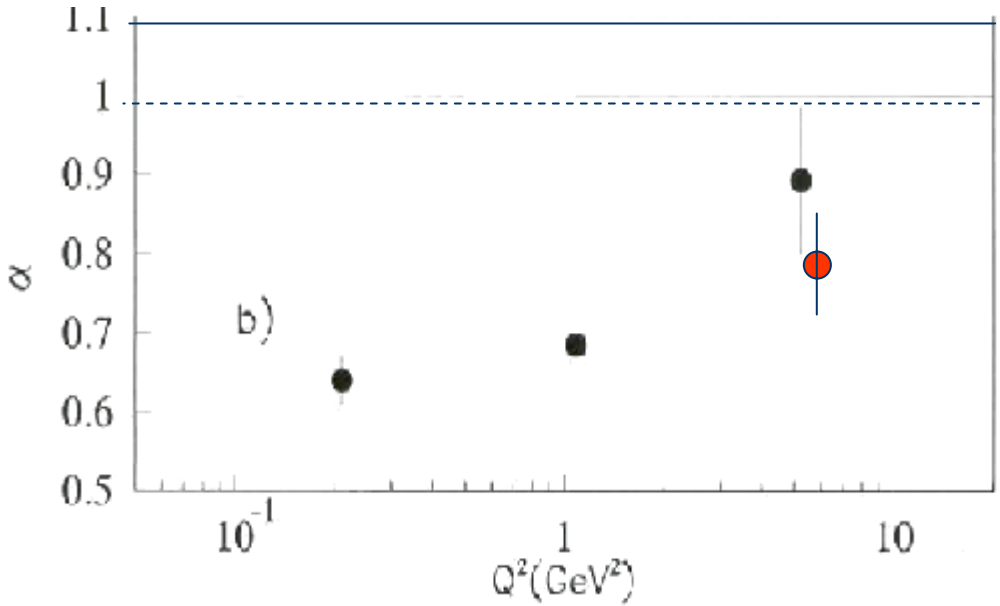


Glauber

with CT

Incoherent ρ^0 Meson Production

FNAL $A(\mu, \mu' \rho^o)$ with E_μ = 470 GeV, A = H, D, C, Ca, Pb



$\mu + A \rightarrow \mu` + \rho + X$

Fit to $\sigma = \sigma_0 A^\alpha$

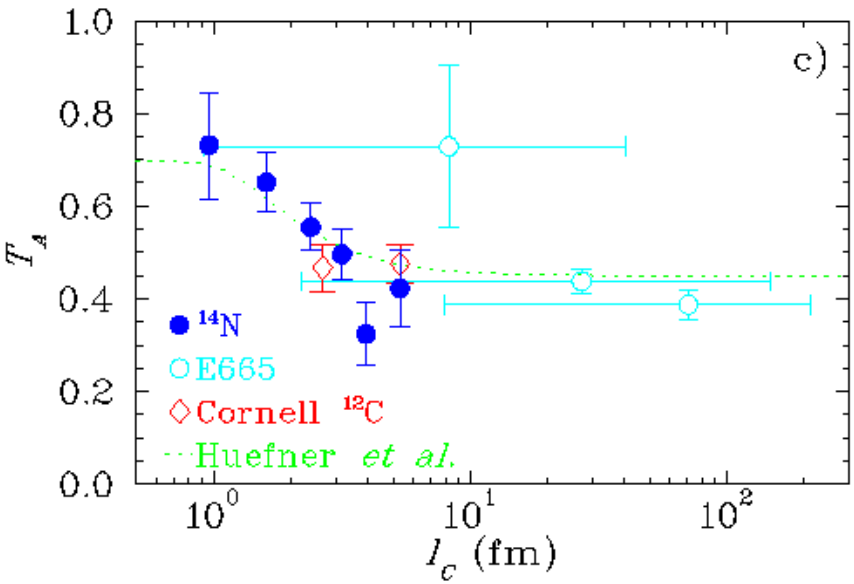
Evidence for CT statistically less significant with NMC data

FNAL E665: Adams *et al.*, PRL **74,** 1525 (1995)

NMC: Ameada *et al.*, NPB **429,** 503 (1994)

Incoherent ρ^0 Meson Production

HERMES (e,e' ρ^o) with E_e = 27 GeV, A = D, ^{3}He, ^{14}N



Transparency vs coh. length

l_c distance in front of the nucleus the virtual photon fluctuates into a ρ^o.

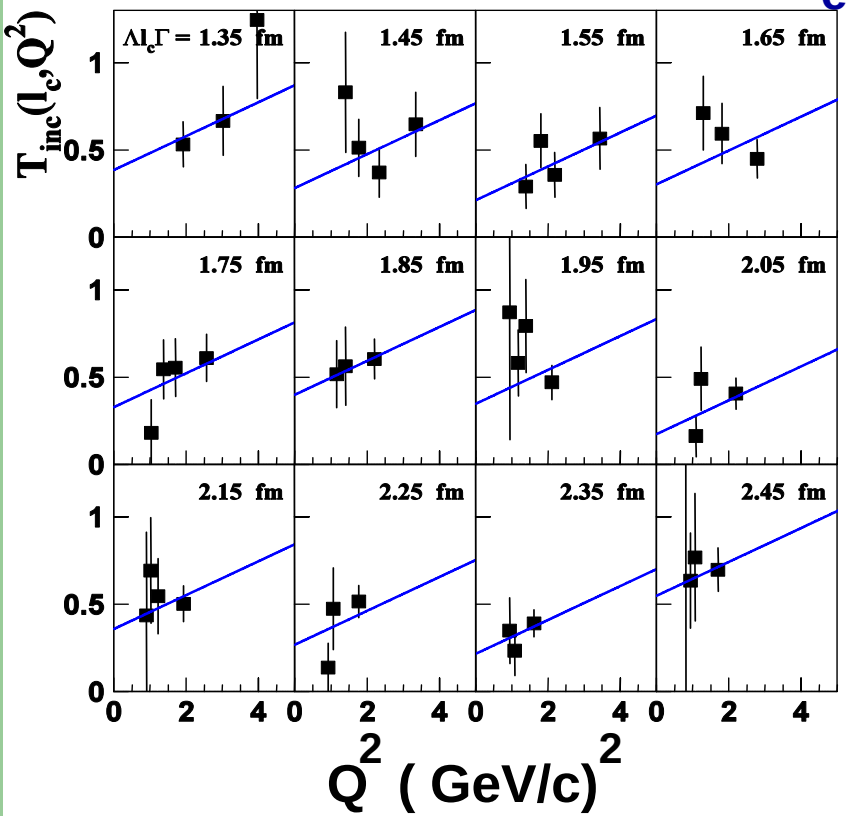
$$l_c = 2\nu / (Q^2 + M_{qq}^2)$$

Evidence of coherence length effect, can be confused with CT a formation length effect.

Akerstaff *et al.* , PRL **82,** 3025 (1999)

Incoherent ρ^0 Meson Production

HERMES (e,e' ρ^o) with E_e = 27 GeV, A = ^{14}N



T as a function of Q^2 for fixed l_c has a slope consistent with CT.

2.5σ deviation from traditional calculations

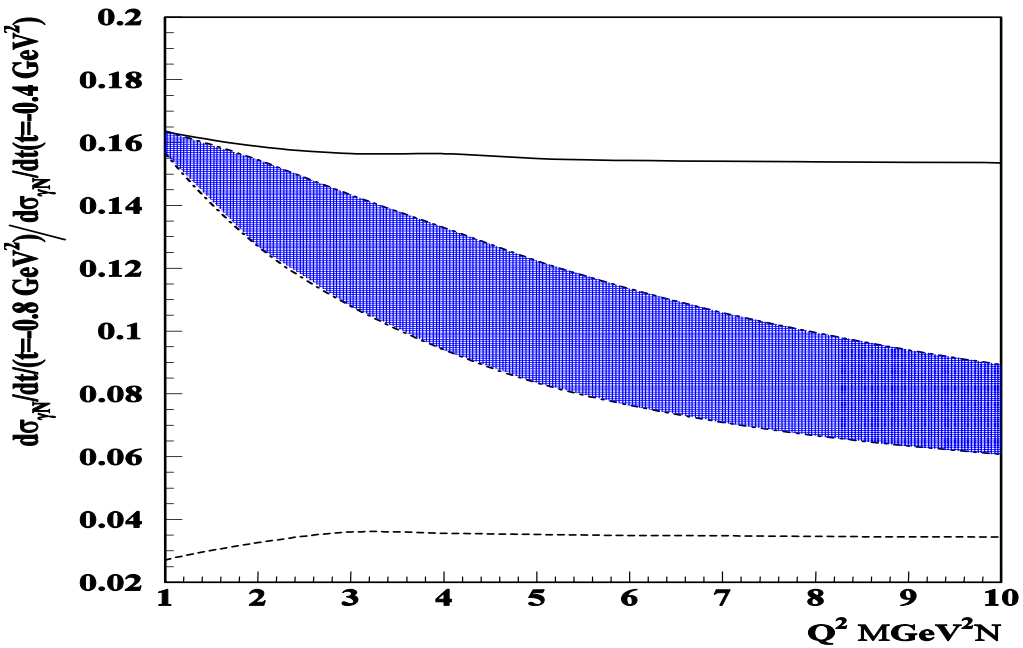
A. Airapetian *et al.* , PRL **90,** 052501 (2003)

ρ^0 Meson Production at Fixed l_c

Ratio of the differential cross-section at fixed l_c, but different *t* : one in the double scattering region and the other in the screening region.

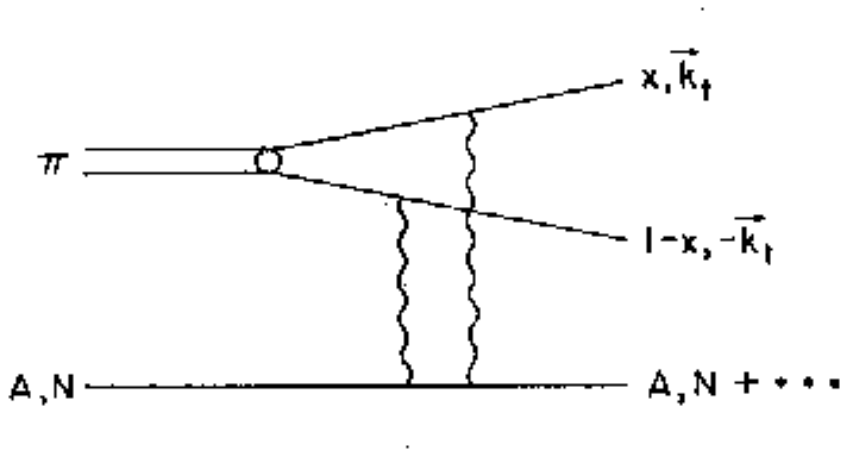
$-t_1 = 0.8\ (GeV/c)^2$

$-t_2 = 0.4\ (GeV/c)^2$



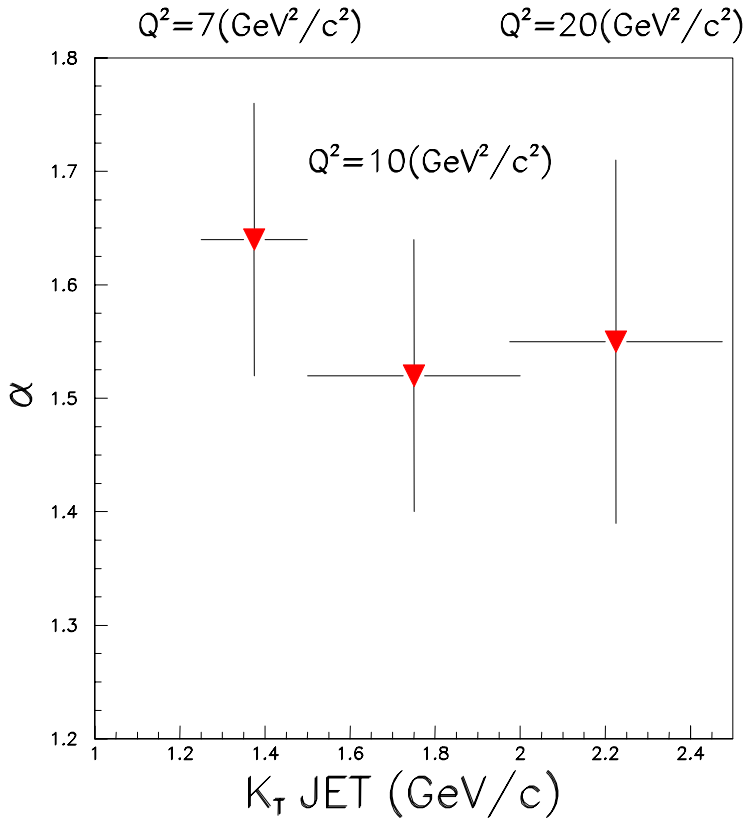
A(π, dijet) Data from FNAL

Coherent π diffractive dissociation with 500 GeV/c pions on Pt and C.



$\pi + A \rightarrow (2\ jets) + A'$

A(π, dijet) Data from FNAL



Coherent π^+diffractive dissociation with 500 GeV/*c* pions on Pt and C.

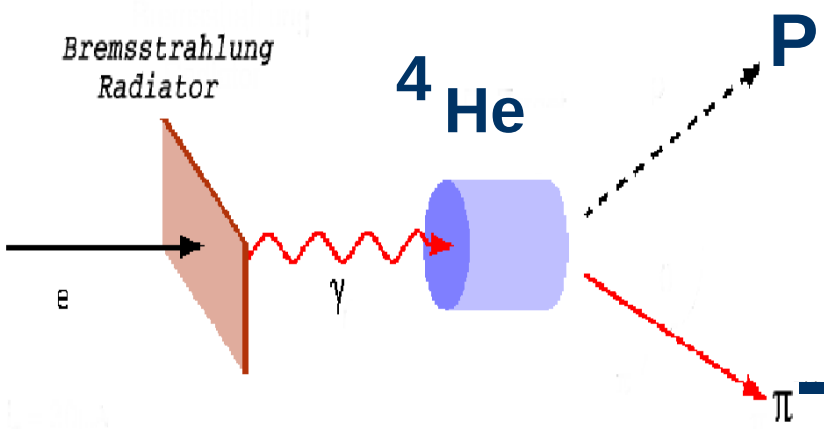
Fit to $\sigma = \sigma_0 A^{\alpha}$

α > 0.76 from pion-nucleus total cross-section.

Aitala *et al.*, PRL **86** 4773 (2001)

Pion-photoproduction

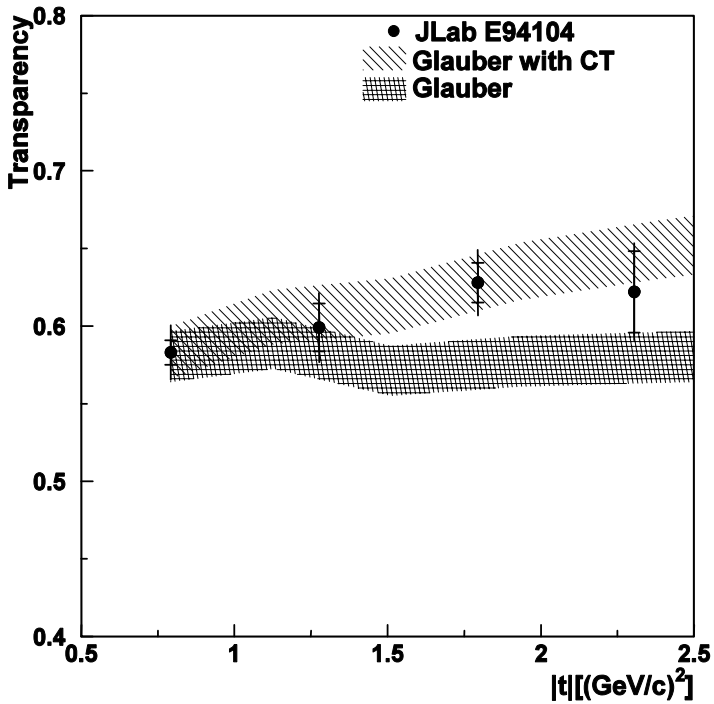
$$\gamma + {}^{4}\mathrm{He} \longrightarrow \pi^{-} + p + X$$



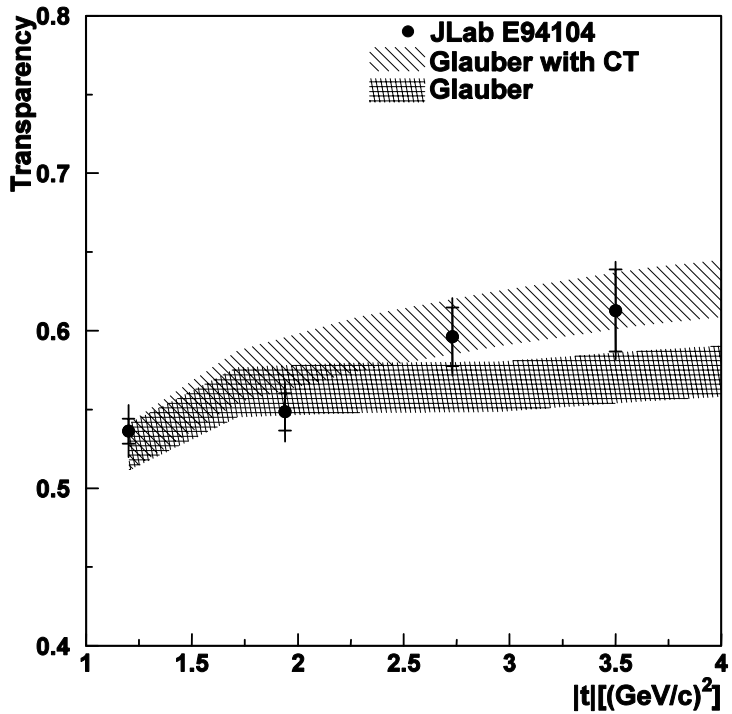
$$T \approx \frac{\gamma + {}^{4}\mathrm{He} \longrightarrow \pi^{-} + p + X}{\gamma + n \rightarrow \pi^{-} + p}$$

Pion-photoproduction

70^0 pion C.M. angle

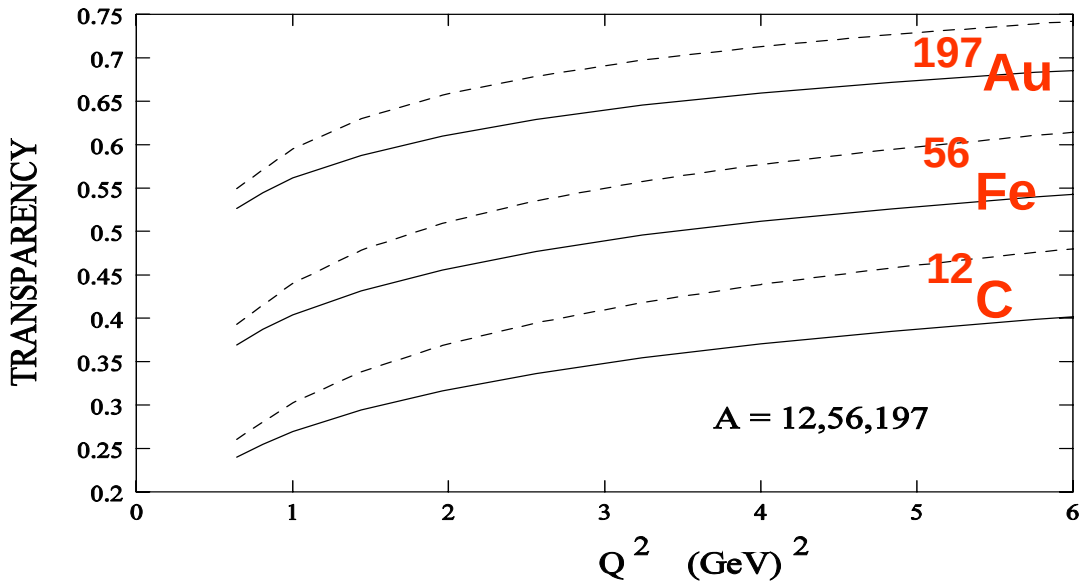


90^0 pion C.M. angle



D. Dutta et al. PRC 68, 021001R (2003)

The A(e,e' π) Reaction



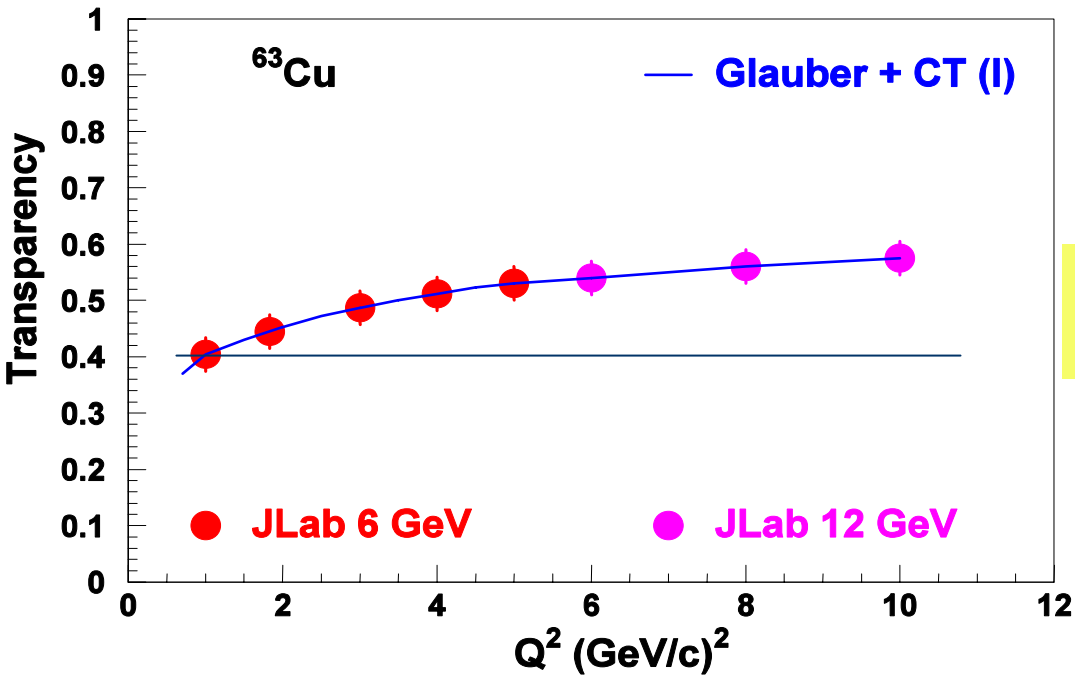
e + A → e + π + X

These predictions are consistent with existing data and independent calculations.

- Most of the CT effect is at $Q^2 > 10\ (GeV/c)^2$
- Two different quark distributions predict effects > 40 % at Q^2 between 1 – 5 $(GeV/c)^2$ for Gold nucleus.

A Pion Transparency Experiment

JLab Experiment E01-107: A(e,e' π) on H, D, C, Cu, Au



Measurable effect predicted for $Q^2 < 5$ (GeV/c)^2

Projected combined statistical & systematic uncertainty of 5 – 10 % and the combined A & Q^2 effect measurable.

Summary

- **Exclusive processes are crucial in studying the transition from the nucleon-meson to the quark-gluon picture.**

- **Comparing exclusive processes on both nucleons and nuclei, one of the signatures of this transition – namely color transparency can be studied.**

- **Experiments at JLab have provided some useful clues .**

Summary

- With the proposed upgrade of JLab to 12 GeV along with the results obtained at 6 GeV we should be able to make significant progress in identifying the energy threshold for the transition from quarks to nuclei.